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A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid

K.S. Reddy [a,*], Madhusudan Kumar [a], T.K. Mallick [b], H. Sharon [a], S. Lokeswaran [a]

[a] Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall EH10 9EZ, United Kingdom

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ABSTRACT

Smart grid is a technology for reliable integration and intelligent control of multiple generation units where the loads spread across a non-uniform or a uniform distribution network. The basic frame work of a smart grid is made to ease the complexity of integration of Distributed Renewable Energy Sources (DRES) with greater grid penetration, reduction of transmission losses, optimized energy capacity expansion with better demand side management and hierarchical control for grid security. Smart grids consists of four unique features which can be given as Integration, Control, Communication and Metering (ICCM). Integration refers to connection of heterogeneous type of energy sources with AC or DC grid using appropriate converters. Power output of the DRES is dependent on climatic conditions like wind speed and solar irradiance. Controls in smart grids are made intelligent to extract the maximum power from the sources, operational scheduling of energy sources and overloads, control of transients, real and reactive power. For effective operation of the diverse smart grid, communication between various control nodes is necessary. Communication standards for smart grids usually are set by protocols, and most of them involve the interconnection of Secure Communication Line (SCL) to the main control unit by LAN (Local Area Network), HAN (Home Area Network), and WAN (Wide Area Network). The interconnection should be accompanied with a firewall at various levels for the cyber security of the smart grid. Smart metering employed in smart grids provides additional information of the electrical energy consumed compared to conventional energy meters. Smart metering can measure the energy parameters of the load remotely and transfer the data through the communication network. This paper presents different methods of ICCM in smart grid.

Contents

* Corresponding author. Tel.: +91 44 2257 4702; fax: +91 44 2257 4652.
E-mail addresses: ksreddy@iitm.ac.in (K.S. Reddy), t.k.mallick@exeter.ac.uk (T.K. Mallick).

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1. Introduction

1.1. Conventional grid and the need for smart grid

The conventional electric grid is a network that acts as a link for transmission, distribution and control of electric power from power producers to consumers [1]. Industrialization and increasing population necessitates the demand for a resourceful and reliable power grid. The energy consumption rate has been expected to increase as shown in Fig. 1 which may result in increased failures of the grid during peak load hours [2]. These power disturbances will result in additional expenses (USD 25 to 180 million) every year [3]. The existing power grid does not meet the needs of the twenty-first century, because of increase in power demand, complexity in managing the power grid, generation and capacity limitations. Therefore, there is an immediate need for the development of highly reliable, self-regulating and efficient grid system which will allows the integration of renewable distributed power generation (to reduce the dependence on fossil fuel and to reduce emissions).

1.2. Smart grid

Smart grid helps the power utilities and grid to have a digital intelligence to the power system network. Smart grid comes with smart metering techniques, digital sensors, intelligent control systems with analytical tools to automate, monitor and control the two way flow of energy during the operation from power to plug. Smart grids are often referred as 'Energy Internet' or decentralized system that turns the electric power infrastructure into two way network build on a standard Internet Protocol (IP) network [4]. Smart grid uses a large number of smaller discrete distributed plants instead of single high-producing plant, it reduces the risk of attacks and natural disasters. Even if it occurs, the smart grid being a self-healing network will restore itself quickly by isolating the particular line and rerouting the power supply. This will be done by using intelligent switches, e.g., rapid digital protection against short-circuit regimes in transformer windings [5]. The large discrete data available from advanced sensing, computing, and communication hardware helps smart grid in addressing power delivery constraints and disturbances.

1.3. Compatibility of smart grid for renewable energy power distribution

Smart grid in renewable energy scenario offers many DRES plug and play convenience and have the ability to accommodate the new demands for electricity by interfacing the local generation units in radial networks [6]. Smart grids comes with the flexibility of controlling distributed generation with voltage regulation capabilities for higher penetration of DRES into generation system [7]. Smart grids have responsive, frequency controlled loads to enhance grid reliability. Integration of small scale Renewable Energy Sources (RES) causes problems like voltage fluctuations, harmonic distortions and requires synchronization of the sources with the grid [8]. Smart grid optimizes these problems by preventing outages and allowing the consumers to manage energy usage. This technology enables various options to add energy to grid at transmission and distribution levels by distributed generation and storage.

Due to the abundant nature, the Wind and Solar power resources are mostly used renewable technologies and are intermittent increasing the need for energy storage. Smart grid is compatible with electric vehicles to use electric cars as energy storage by drawing power from the charging cars when demand is peaking to mitigate peak load [9]. The combination of renewable energy generation systems along with PEVs/PHEVs plays a significant role in operational cost and environmental influences in terms of reduction in petroleum consumption and carbon dioxide

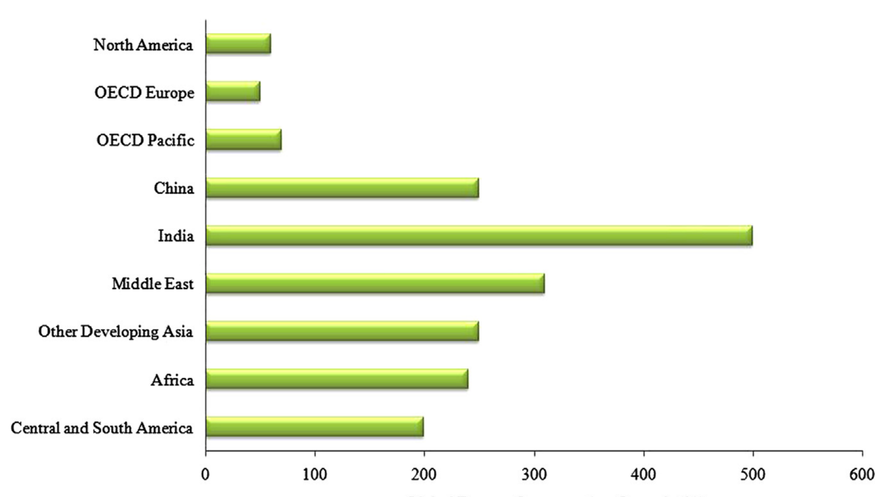

Fig. 1. Predicted global energy consumption growth from 2007 to 2050 [2].

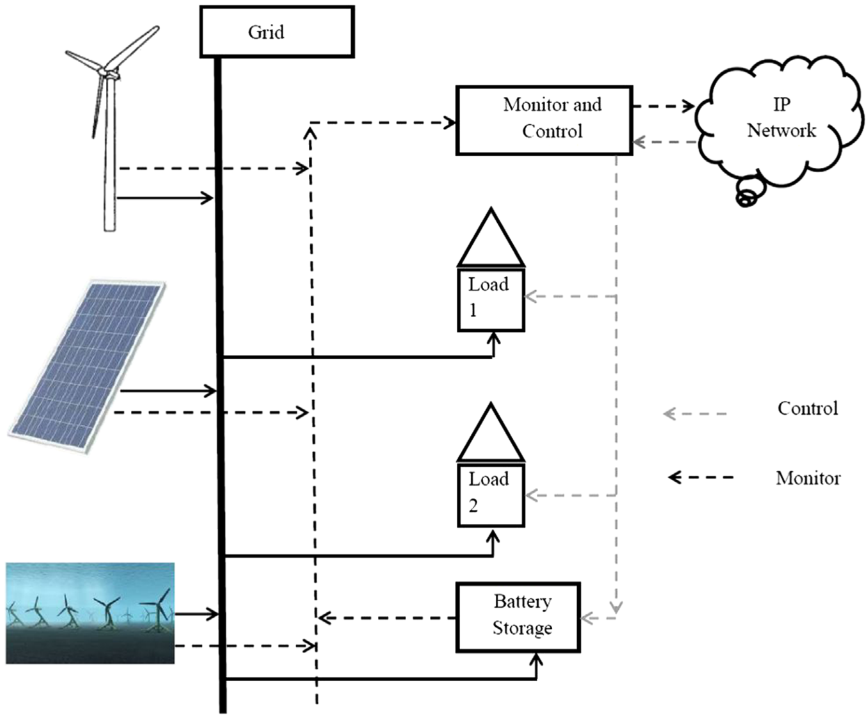

Fig. 2. Power supply unit with renewable energy supply, battery storage, a smart controller, load balancing capabilities, and a grid tie connection [12].

emission [10]. Related technologies like thermal storage for cooling or combined heat and power can also reduce peak and overall demand [11]. One such system [12] consisting of three distributed generation systems, Wind, Solar and Tidal and utilizing commercially available energy storage and a smart-home management controller was implemented in Roqoe island. The schematic diagram of the system is shown in Fig. 2.

Smart grid offers high penetration to the DRES (extent to which DRES supply can meet the electrical demand) thereby reducing the duration of operation of gasoline based generators resulting in reduced CO_2 emissions. Pacific Northwest National Laboratory, USA estimated indirect reduction of 525 million metric tons (18% of US total) by the year 2030 [13]. European Technology Platform (ETP) blue map scenario estimates annual CO_2 reduction by 0.7Gt to 2.1Gt of CO_2 by 2050 in Europe [14].

Phuangpornpitak and Tia [15] reviewed the opportunities and challenges of integrating renewable energy in smart grid system. Siano [16] reviewed the role of demand response in smart grid and the associated technologies. A comprehensive review on different load classification algorithm in application to smart grid is given in [17]. The role of cloud computing in developing solutions to smart grid is given in [18]. The present paper deals with the current research progress in Integration, Control, Communication and Metering of smart grid in particular importance to renewable energy. The results of various studies in the above mentioned area has been discussed briefly which will be useful for researchers working on renewable energy source integrated smart grid.

2. Integration of renewable energy sources to smart grids

Modern Renewable Energy Systems (RES) include integration of Photovoltaic (PV), Biogas Generators (BG), Wind Generators (WG), Distributed Generators (DG), multiple storage systems and control methodology for the load scheduling. Gupta et al. [19] suggested a system for integration of RES and storage system to form a hybrid energy system (HES) as shown in Fig. 3.The distributed generators considered are Photovoltaic systems, Concentrated Photovoltaic systems, Biogas Generators, Diesel Generators, Wind Generator and Micro Turbines which are connected to load bus after power processing.

2.1. Photovoltaic (PV) and concentrated photovoltaic (CPV) system integration to the grid

PVs and CPVs are solar irradiance dependent sources of power. Compared to PVs, CPVs offer higher efficiencies and can be used for production of both electrical and high-grade thermal energy [20]. The PVs have 1 sun solar concentration however, the CPVs at present are tested for 500 sun solar concentration using optical dishes [21] e.g., a 20 kW Integrated High Concentration PV (IH CPV) installed in Arizona [22]. StarGen™ tested Concentrated Photovoltaic dense array system with 12 m^2 solar concentrator cells with concentration levels of 2500 suns, without any series resistance problems. The system had Vertical Multi Junctions (VMJ) with 40 series connected junctions providing 40 times voltage and 1/40 times current of similar size silicon concentrator cell design, with I^2R losses reducing to 1/1600th times [23].

PVs and CPVs connected to the grid have problems such as negative power quality impacts e.g. voltage fluctuations, power factor changes, frequency regulations and harmonics [24]. Effective regulation of power quality is essential at generation level (at the point coupling of multiple energy sources) and consumer level (at point of load distribution networks) [25]. IEC 61850-7-420-9 (Distributed Energy Sources) refers with the standards to be followed for connecting several PV units with storage technologies [26]. PV/CPV arrays can be connected to the grids after extracting their maximum power by MPPT [27] using a DC/DC converter. Conventional DC/DC converters have 5–6 times boost factor resulting into extreme duty cycle degrading overall efficiency. A soft commutation technique using ZC-ZVS for active and passive switches of DC–DC converter was proposed by Al-Saffar et al. [28] for high boost factor with reduced switch stresses. Integration of PVs and other DC generator to a DC grid is easy and

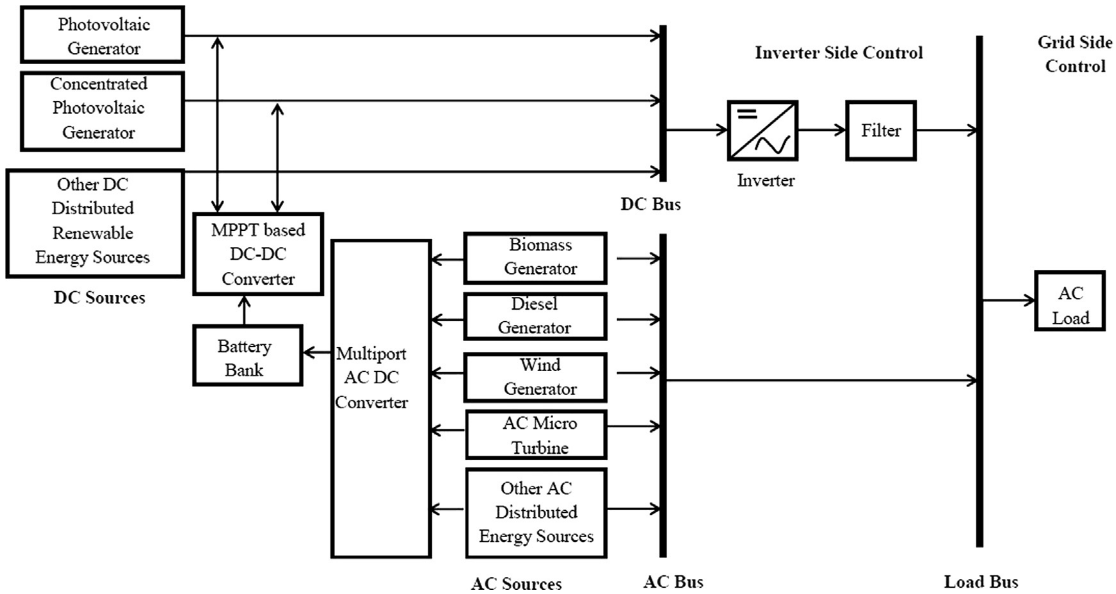

Fig. 3. Integration of sources to the battery storage system and buses [19].

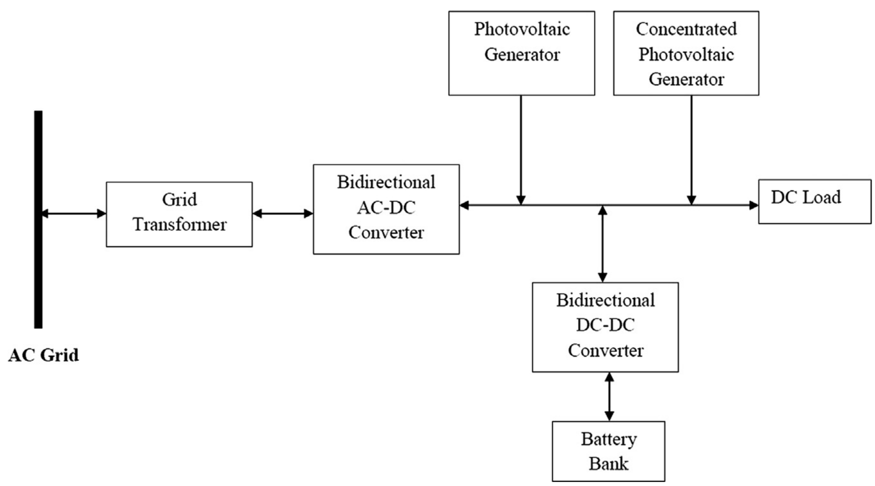

Fig. 4. Integration of PV and CPV to the DC loads [30].

efficient compared to an AC grid owing to the fact that conversion losses in DC grid are less and there is no need of DC/AC converters, which makes the system cheap [29]. The impedance of DC lines are less but appropriate DC voltage regulation is required. Integration of PV with the DC loads is shown in Fig. 4 [30].

Grid side control in AC grids is used to transfer power from the DC link between the DC–DC converter and the inverter of the AC grid. DC link voltage is taken as reference for controlling the firing angle of grid side inverter to regulate the grid parameters. A multivariable state space model with a linear quadratic regulator (LQR) was used by Alepuz et al.[31] for control of complete system (DC link, Inverter, Filter and Grid side control). Inverter sizing was done using a financial model to reveal the impact of different inverter sizes to maximize the financial return [32].

PVs and CPVs are interfaced to a DC–DC converter with MPPT. A bi-directional DC–DC converter is used for both charging and discharging of the battery during charging and discharging states respectively. A bi-directional AC–DC converter was used for charging the battery to transfer power from main AC grid to the battery or to the DC load during low solar irradiation. During the excessive solar power output from the PVs and CPVs, the power can be exported or sell to the main AC grid. A hybrid DC/AC integration method to establish a micro grid for continuous energy mixing strategy for DC integration of local generation and grid energy to supply energy to the micro grid consumers via three phase power distribution was simulated by Karabiber et al. [33] and is shown in Fig. 5. All the power generated by the AC and DC sources was converted to DC and then converted back to three phase AC as shown in Fig. 5. By this way, the local distributed generators do not have AC integration problem such as AC stability and line synchronization. The benefits of integrating renewable energy to the grid is shown in Fig. 6 [34].

2.2. Integration of distributed AC generators to grid

Biomass Generators are most commonly used AC Generators in renewable smart grids, due to its compatibility with dispersed community loads e.g. 10 kW generators tested in sub-Saharan Africa [35] and 100 kWe biogas plant in Tumkur, Karnataka, India [36]. Due to its weather independent nature and abundance of plant biomass like bagasse [37], algal resources [38] and animal feces [39], Biogas Generator can always provide a fixed base line load [40]. Diesel Generators integrated with Wind Generators operated in asynchronous operation can deliver constant

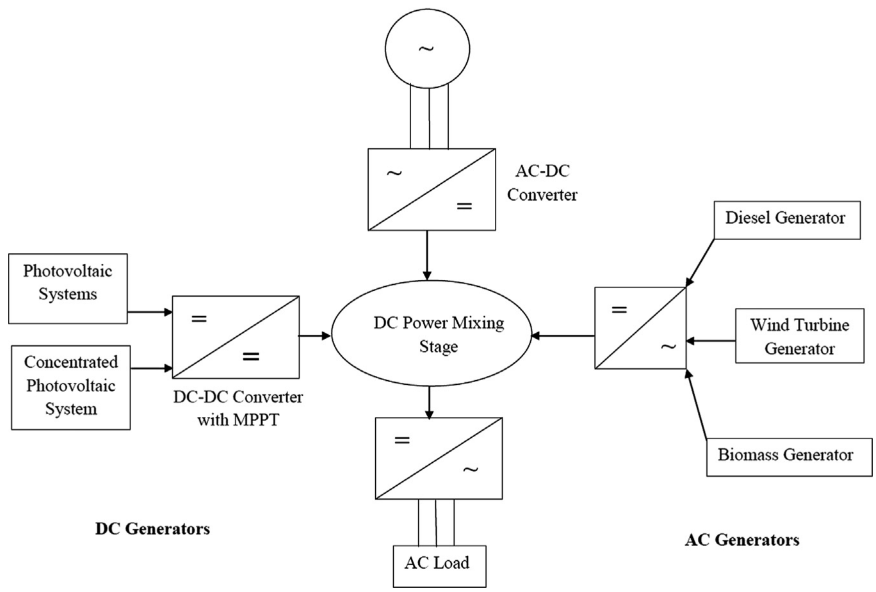

Fig. 5. Hybrid DC and AC sources integration technique [33].

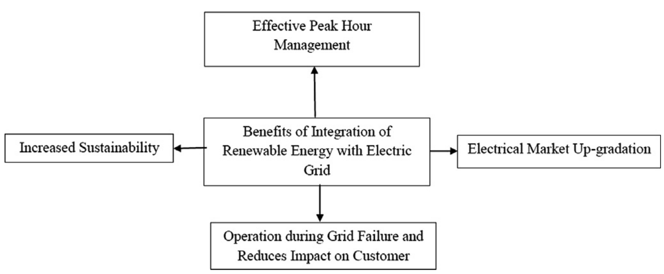

Fig. 6. Benefits of renewable energy integrated electric grid [34].

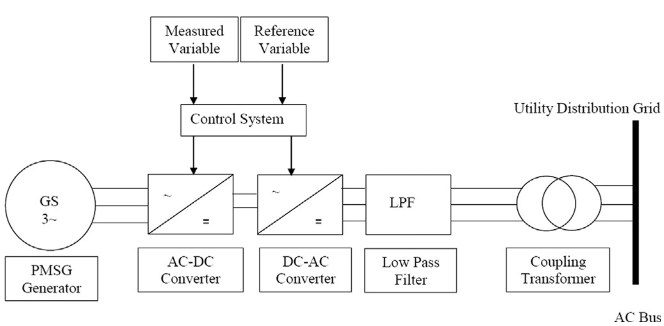

Fig. 7. Integration of PMSG wind generator to the utility grid (AC bus) [44].

frequency electric power to grid and can save considerable amount of fuel [41]. Similarly, Biogas Generators can be integrated with wind turbine. When the wind speed is below the operation level of wind turbine biomass generators are turned on. Intelligent controller was used to adjust the gas flow valve to control the power generation of biomass generator [42]. In case of direct integration of AC generators to DC grid output from the generators is converted to a grid DC voltage before connecting it to the DC grid [43].

A method to integrate wind turbine with a Permanent Magnet Synchronous Generator (PMSG) to the utility grid was demonstrated by Molina et al. [44] as shown in Fig. 7. The Power Conditioning Unit (PCU) is composed of three phase rectifier bridge (AC/DC conversion) and a power inverter (DC/AC conversion) built using three phase, three level impedance source (or impedance fed) inverter design (z source inverter). Similar methodology is adapted for integration of other AC generators to the AC grid (Biogas, Diesel and Micro Turbine Generators). But, the presence of multiple AC generators can add additional reactive power needed for the generator making the grid itself a VAR burden and drop in Power Factor (PF). A voltage source inverter with a Phase Locked Loop control (PLL) was proposed in [45] to maintain the coherence between the grid reference frequency and measured frequency of the grid. Also, multiple AC generators can create the problem of inter area oscillation [46] where generators located in one part of grid oscillate with other. Wide area measurements could be used and intelligent control can be incorporated for the same.

Connection of generators in the network depends on the type of the line i.e. Low Voltage (LV), Medium Voltage (MV) or High Voltage (HV). As per Spanish legislation [47], the generator capacity should be 50% of sub-station capacity with permissible voltage unbalance of 3–5%, and frequency set of 60 Hz with variations between 59.7 Hz and 60.2 Hz. The phase to neutral voltage was set at 85% and 110% of rated value.

2.3. Integration of Battery Energy Storage System (BESS) to grid

Renewable energy grids with storage systems achieve marginal economic performance [48] and better operational efficiency [49]. Energy Storage systems acts as an energy buffer to mitigate the impacts of fluctuating output of DERs [50]. A Hybrid Energy Storage System (HESS) in a smart grid consists of both electrical and mechanical storage systems. The storage systems should have high energy density and should be governed by Energy Management Systems (EMS). The HESS can be categorized into (1)Mechanical systems (Pumped hydro, Compressed air energy storage, Flywheels); (2) Electrical systems (Capacitors, Ultra capacitors, Superconducting magnetic energy storage); (3) Chemical/ Electrochemical systems (Metal-Air, flow batteries, Li-ion batteries, NaS battery, Hydrogen energy Storage). Ideally, the battery must perform many charge/discharge cycles and recharge must be possible in short period of time with minimum energy [51]. Ultra capacitors can be used in renewable energy grids since, they have a higher energy storage density of around 10^4 to 10^7 W/kg compared to 10 W/ kg to 1000 W/kg [52]. Vanadium Redox Batteries exhibit efficiencies

of 80% and current densities of 80–100 mA/cm^2 [53] with current efficiencies of 20 Wh/l with 65–75% efficiency and 12,000 charge/discharge cycles [54]. Lead Acid Batteries are deep discharge batteries and can be used to power the grid for longer duration even at discharge depth of 100%–130% [55]. Ni–Cd (Nickel Cadmium) Batteries can be opted for electrical storage and they can provide pulsed power due to their low Equivalent Series Resistance (ESR) [56]. Batteries are connected to the grid using bi-directional DC–DC converter to perform the charging and discharging operation based on the State of Charge (SOC).

3. Control systems in smart grids

3.1. Operation scheduling of energy sources and loads

Demand Response (DR) is like dynamic demand mechanism to manage customer consumption in response to electric power available for consumption. The Demand Response (DR) and the Demand Side Management (DSM) optimizes [57] the power flow in the network, regulates the voltage profiles by acting on the reactive power flows across the substation, minimizes losses and reconfigures network and storage systems. A method of load profile reformation using the pricing elasticity was suggested and tested on Iranian smart grids [58]. This method was based on the self-elasticity and cross-elasticity based pricing which allowed end users to control the power consumption in peak hours. Iranian grids showed a reduction of peak load by 8% for 100% consumer participation in demand response program [59] and it has been assumed to increase the demand response potential by 40% [60]. Demand response program was performed on 33 isolated power stations in Queensland, Australia [61] for scheduling of Geothermal and solar sources to shift the load from peak hours to off peak hours using load economic model with price elasticity. Demand Side Management program are of three types namely Economic/Market driven, Environmental driven and Network driven for power network stability.

New York ISO (NY ISO) has four generic types of DR [62]:

a) Emergency Demand Response Program (EDRP): EDRP enhances the Available Transfer Capacity (ATC) which is a measure of transfer capability in the physical transmission network. EDRP was run on IEEE30 bus system [63] and EDRP was performed on buses with higher sensitivity. EDRP performs load shifting by allowing utilities to shed some of the loads in the peak hours by giving monetary compensation [64].
b) Day Ahead Demand Response Program (DADRP): Energy price is declared a day ahead. If the user consumes more than the base line that day, excess tariff is implemented to curtail consumption.
c) Installed Capacity (ICAP) Special Case Resource (SCR): Similar to EDRP but used to displace an expensive resource for economic reasons in emergency.
d) Demand Side Ancillary Service Program (DSASP): The solutions offered under this category are [65] Regulation (Power sources adjusts itself every minute to fluctuations), Spinning Reserves (Power sources adjusts itself every 10 min) [66], and Supplemental Reserves (similar to spinning reserves but with larger response time).

ISO-NE (New England) [67] implemented a standard market design with DR having two programs: (a) Price Response Program (PRP): Consumers can control their load consumption based on the price tariff at an hour and (b) Real Time Demand Response Program (RTDRP): Internet based communication system open solution (IBC OS) for collection of real time data to perform the DR program.

Generation scheduling problem was solved by partitioning it into sub-problems where artificial constraints were used to form a Lagrangian functions [68]. An intelligent scheme consisting of both Artificial Intelligence (AI) and mathematical tools based on Multi Agent System (MAS) was proposed for energy source rescheduling [69,70] in an islanded power system with DRES and lumped loads shown in Fig. 8. The objectives of MAS are (a) Each micro grid should fulfill its own internal demand, (b) Micro grid should obtain possible ways of exporting the power to other network and (c) Rescheduling the micro grid to fulfill overall demand. Each distributed resource is treated as an agent and connected to the communication interface for computation.

Agents have inertia to respond to any change in grid balance conditions. The decisions of agents are taken after gaining the knowledge base from a database. A knowledge based system which has set of predefined rules for particular condition which interprets the decision. The action simulator then, assigns the state of each distributed generators. A micro grid was differentiated into a three-store network to look analogous to a cloud computing structure [71]. A cloud computing involves the Cyber Physical System (CPS) which smartly integrated the computing power, communication ability and autonomous control capability. Game theory was specifically used for the Demand Side Management by Rad et al. [72] where players are the power consumers, and the their strategies are the energy consumption. Based on the strategy of the players (energy consumption of the consumer) the power

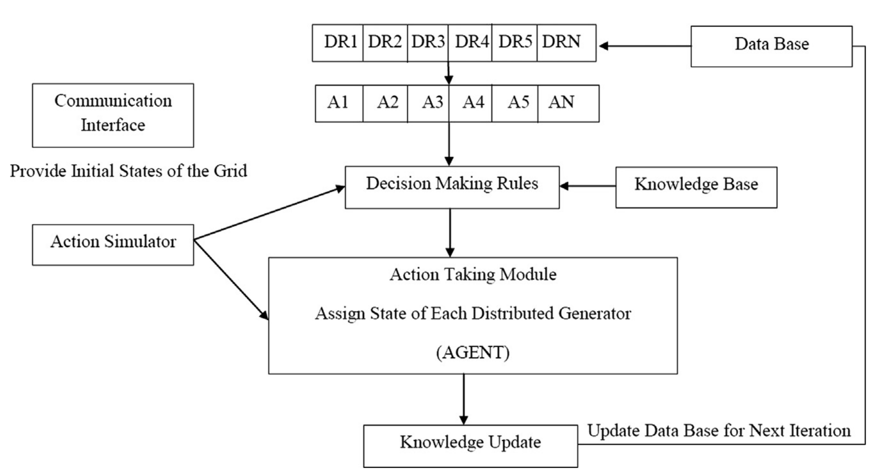

Fig. 8. Multi agent system based energy scheduling [69].

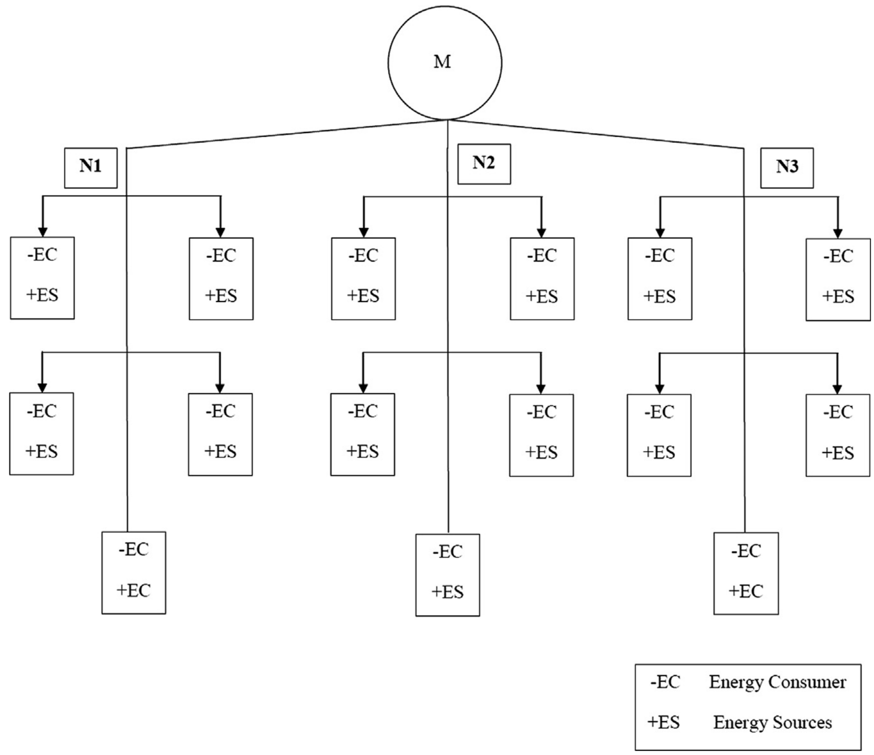

Fig. 9. Energy flow networks for scheduling in smart grids [81].

utility company can vary the price tariff at specific time interval. An intelligent Decision Support Structure system was studied by Guan et al. [73] for power dispatch which includes the assessment of the security, and decision making of the control system for ensuring quality power dispatch. The state of the grid was hence made to correlate with the decision making support systems of the smart grid.

Another method, suggested by Gimaccia et al. [74] for the Demand Side Management was using artificial intelligent prediction tool (Artificial Neutral Network) for forecast of energy generation which can be given to the control system for day ahead scheduling. Fuzzy Logic was used to determine the weight of the neural network for hour ahead and day ahead forecasts. A method for scheduling the generators using data mining tools for forecasted day ahead power generation model was suggested by Moghaddam et al. [75] with an objective to minimize heating losses, CO_2 emissions and fuel consumption by the generators. The objective was minimized by a Non-Dominated Sorting Genetic Algorithm II (NSGA-II). For multi-operation management a multi objective Adaptive Modified PSO (AMPSO) was proposed with a Chaotic Local Search (CLS) approach to find the best local solution and a fuzzy self-adaptive mechanism to adjust the PSO parameters.

Decentralized control method for shifting loads (where loads do not have significant impact) was suggested by Ahn et al. [76]. A centralized Control scheme was discussed by Planas et al. [77] at Grid level, Management level, and Field level. The hierarchical control is done to effectively manage the import and export real and reactive power, estimation and control of the grid parameters and for islanding operations, restoration of amplitude and frequency deviations produced at the field level and transfer of micro grid from the islanding to grid connected mode.

Another method of smart scheduling of the dynamic load control was proposed by Liu et al. [78] based on the priority ranking which where each of the utility user had a different priority class. A weighted utility function was adopted to determine load reassignment. Utilization of electric power was dependent on factors namely redundant rate, variation rate and transmission loss rate. Event driven simulation method was used on ten numbers of generation units and large number loads with assumption that generators and loads were randomly distributed. Smart metering was used for collection of data of various users and can be sent to the generation units. For load control scheme, initially all the weights were assumed same. Each electric generation unit periodically collects the real time data from its users and calculates the value of the cost function and the information obtained from other electric generators and will reassign the electricity among users. A cost function based method was used for dynamic load control scheme to improve the utilization of power.

Method of multi-layer optimization control was demonstrated by Cisco [79] where grid control for scheduling energy sources was solved by dividing it into a master problem (global solution) and sub problem (local solution), where sub problem was controlled by the master problem [80]. A tree like User Mode Network (UMN) architecture corresponding to demand side loads was proposed by Alagoz et al. [81]. UMN comprises the end user nodes which are interconnected in tree like hierarchical network as shown in Fig. 9. End users or nodes can take either Energy Supplier (ES) mode or Energy Consumer (EC) mode. Generated energy flows upward and energy flow for consumption is downward. In UMN architecture, all generators and consumers are placed at the bottom of a tree like node hierarchy as end users. Energy flow is controlled by the nodes in both the direction from bottom up for energy export and from top down for energy import.

3.2. Control of overloads in smart grid

Grid overload occurs when the generated power is less than the actual load. The Battery Energy Storage System (BESS) can be used for Energy Management Systems (EMS) [82] to operate the Battery Management System (BMS). The Battery Management Systems

(BMS) increases the storage lifetime of BESS [83] by splitting the battery bank into several strings that are connected in parallel. Based on the current State of Charge (SOC), the state of health, battery management system enables shorter cycles at low State of Charge (SOC), increases the battery current rate and intensively fully charges the battery in normal conditions. In case of BMS systems Ah balancing was done to determine the SOC for BMS operation. Ah balancing with variable losses over a large time was proposed by Duryea et al. [84] and can be used for the BMS unit for controlling overloading conditions. Field trials for checking the effectiveness of the storage systems for voltage control, power flow management and restoration was done by ABB in Great Britain [85] on a 11 kV system.

Fast response characteristics of fuel cells was proposed in [86] for damping out the oscillations in the grid due to frequent change in load and generation in the smart grid. Two loops, one for voltage control and another for phase control was used and switches of inverter were controlled for phase and voltage control. Method of intentional islanding for operating selected generators during overloading was proposed by Chen et al. [87]. Integrated Micro Generation Load and Storage Functionality (IMLS) was adopted for Medium Voltage (MV) lines by Vasiljevska et al. [88] for: (1) controllable micro grid dispatch, (2) Controllable load shift and (3) controllable energy dispatch for the Distributed System Operator. Another method to prevent overload was suggested to have Building Integrated Photovoltaic (BIPV) [89] where the PVs are hinged as walls of building and acts as local generators.

3.3. Control of transients load in smart grids by Hybrid Energy Storage Systems (HESS)

Smart grids when connected to RES have to face the problem of transient loads. A Super Capacitor (SC) and a Vanadium Redox Battery (VRB) were connected together forming a HESS to the DC grid using a Bi-directional DC/DC converter (BDC) was proposed by Etxeberria et al. [90]. The simulations were carried out for the PI controlled and Sliding Mode Controlled (SMC) DC/DC converter. The PI controlled BDC shows good response in the operation region whereas the SMC based BDC offered good transient response at sudden load variations.

The SC and the VRB can be connected to grid in a number of ways. Three such methods were simulated in [91]. The three topologies simulated were Parallel Active Topology, Floating Topology and Three Level Neutral Point converter (3LNPC). These topologies help in smoother power distribution among the SC and VRB. 3LNPC offered reduced power loss up to 52.8%, Parallel Active Topology offered 39.65% reduced power loss compared to Floating Point Topology.

3.4. Active power versus frequency (P–f) and reactive power versus voltage (Q–V) control on grid due to AC generators in smart grids

P–f (Active Power versus Frequency) and Q–V (Reactive Power versus Voltage) control involves the variable slope coefficient of droop characteristics for calculating the load fluctuation. By calculating the quality of load, adjustments are made in the firing angle of the inverter connected between the BESS and the grid to control the active and reactive power at reference frequency [92]. The micro grids formed by integration of RES lacks the load following characteristics i.e. RES do not have inertia. A P–f and Q–V droop controller is essentially a controller which gives inertia to the system by subtracting the average active power and reactive power with the frequency and voltage amplitude and provides the system with inertia. Fig. 10 shows the active power versus frequency response of a grid connected to generator. The relationship between the frequency and the power output of the DG or the

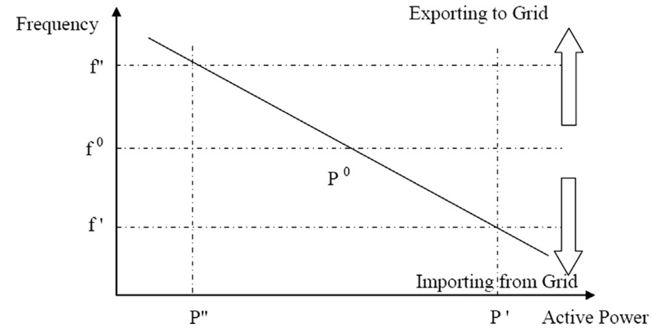

Fig. 10. Active power versus frequency response of a generator connected to a grid [92].

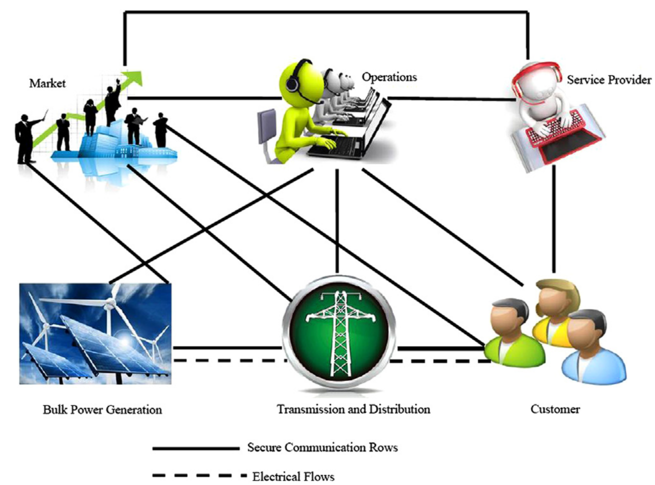

Fig. 11. Smart grid architecture [103].

utility grid is given as

$$f' = f^0 - K^U(P' - P^0), \tag{1}$$

where the K^U is the droop constant, f' and P' are the DG output power at an operating point. f^0 and P^0 are the nominal values.

When the load increases, during islanding operation the DG output power increases and frequency decreases according to the droop characteristics imparting inertia to system [93]. Investigation of small signal and transient stability was carried out by Zhao-Xia et al. [94] on the system for the cases like fault on three phase line of the AC bus and variation of motor load. The simulation results showed that the use of P–f and Q–V droop control enhances the load sharing among the sources in the RES. In order to provide the decoupling control the active and reactive power control cross and an integral component was added across the conventional droop controller [95,96]. Singular Entropy Theory was used to extract the model parameters accurately.

3.5. Active and reactive power management in smart grids

For active and reactive power control on the grid side, power converter control was nested in a two-loop feedback system [97]. The inner loop regulated the current and hence the power quality was maintained. The outer loop based on the voltage feedback is responsible for the flow of power for droop characteristics control. Phase locked loop was proposed for synchronization of the grid.

Reactive power management strategy for the co-ordinate handling of reactive power from the distributed generation units and Flexible AC Transmission Systems (FACTS) units, by applying evolutionary optimization algorithm for finding the optimal location of Static Var Compensators (SVC), for optimum reactive power

injection simulated by Alonso et al. [98]. The method proved efficient in increasing voltage stability by increasing DG penetration level. A method of sensitivity analysis of voltage at nodes to control the reactive power exchanged was simulated by Brenna et al. [99] for reactive power control.

A method of using shunt filters for the compensation of the harmonics, flicker, notches, sags and swells resulting due to the sudden change in the solar irradiation and wind speed was proposed by Neves et al. [100]. The shunt active filters drain the distorted components of the load currents from the grids. The proposed system was tested by connecting 16 PV arrays with total nominal power of 200 W each. The shunt active filter combined with the MPPT was capable of mitigating current harmonics, and simultaneously injecting energy produced the PV arrays to the grid. Power Conditioning Units (PCU) [101] can be used for harmonic current reduction by outputing harmonic voltages equal to the one in the grid.

4. Communication and smart Metering

4.1. Communications in smart grid

The renewable energy power grids have multiple networks with multiple Distributed Energy Resources (DER) and distributed loads. Such a distributed system calls for an effective communication and co-ordination to monitor, analyze and stabilize the grid at various hierarchical levels. The motivation of a smart grid comes from the need to have an improved utilization of power generation sources, increased productivity, adherence to regulatory constraints, enhanced customer experience and lower carbon fuel consumption [102]. The basic architecture of smart grid was proposed by NIST (National Institute of Standards and Technology), USA [103] and is shown in Fig. 11. NIST has standards for communication technology of smart grid like power line communications technology, IEEE 802.15.4 (ZigBee), IEEE 802.11 (wireless LAN (WLAN) or Wi-Fi) and IEEE-802.16 (WiMAX), GSM, GPRS and DASH7. Power Line Communication (PLC) [104] is one such method that uses the existing transmission lines to transmit the high speed data signals from one device to another. A Power Line Communication (PLC) network collects data from line concentrators and the data is transmitted through cellular network. Existing Home Area Network (HAN) can be combined with PLC technology in urban areas. The detailed communication frame work, its architecture, standards and types of wired and wireless communications have been discussed briefly in [105].

The PLC network is noisy and harsh with limited bandwidth of 20 kbps in Neighboring Area Networks (NAN). Smart grid networks have to carry highly varying traffic of data with encrypted security since smart grids are prone to outside cyber-attacks. Due to challenges in the existing HAN which operate at near 2.4 GHz for scientific and medical usage causes the co-existence of interference and noises. The generated data transmitted over the HANs are of the order of terra bytes. Hence, the use of cognitive radio improves the spectrum utilization in case of a smart grid. A cognitive radio was proposed by Yu et al. [106] that potentially utilizes the entire spectrum since, it covers all the spectrums layers: HAN, NAN and WAN. Communication interconnection standards and smart grid interoperability related methods are given in IEEE 2030-2011 for advanced distribution system protection and automation practices [107]. For communication between two power grid control center such as Inter Control Center Communication Control (ICCP), an open and standardized protocol based on IEC-60876-6 and Tele-control Applications service Element Two (TASE.2) can be used [108]. The markets could access the transmission grid using Open Access Same time Information System (OASIS).

4.2. Smart metering in smart grids

Smart metering in a micro grid measures the electrical energy consumed and also provides the additional information compared to the conventional energy meter [109]. In US electricity generation by solar, wind, hydro, anaerobic digester or any other renewable source is eligible for smart metering [80]. Design of a smart meter in a smart grids depends on the requirement of the utility company as well as the customer. A smart meter has several control devices, various sensors to measure the parameters and devices to transfer the data and command signal. Smart meters could be employed to detect unauthorized consumption of electricity theft in the view of improving the distribution efficiency. Smart meters are connected to the database of the utility company by means of a gateway of communication interface protocol. Fig. 12 shows the communications network around a smart grid for smart metering, which consists of a communication devices governed by protocols.

Communication devices gather two way information of measured variables of the smart grids from the bulk generation units, transmission sectors and distribution sectors. This information is

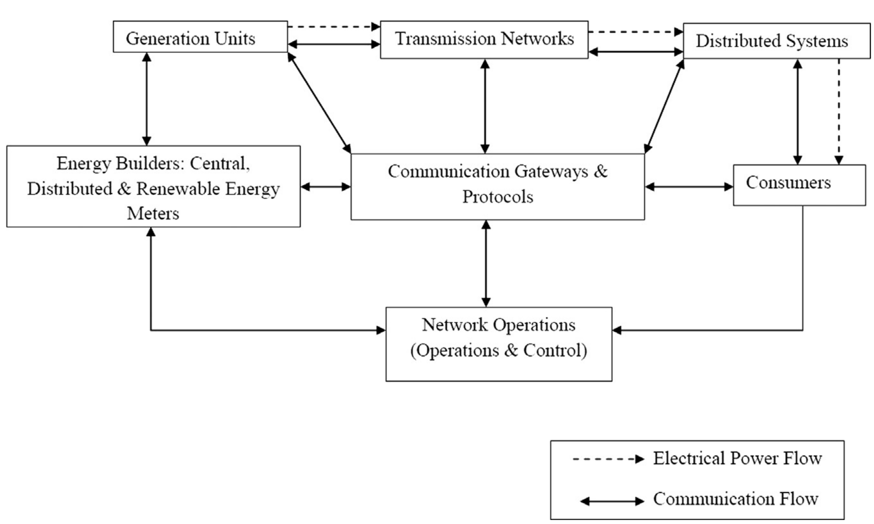

Fig. 12. Communication network in smart metering system [108].

necessary for calculation of generated power and losses in the transmission. Communication devices also monitors the customer devices for control of power generation using networked operation. The networks operations coordinates data and control signals between customers, appliances and utility company. A smart grid system determines the need of aspects such as workflow, workforce management, asset management and billing systematic.

Metering system that controls primarily the generation and load variables like generated power by source and power consumed by the loads was demonstrated in Brazil [110] for prepaid purchase of power. This helps in forecasting and estimation of the load month ahead. The load scheduling can thus be done by finding the system operational costs of various generating units versus energy sales costs of each generating unit. Two energy meters were placed for each of the household utilities. One meter was placed inside the household utility and another energy manager was placed outside the household utility. Based on the load demand measured by the meters, it was ensured to achieve the higher penetration rate for the renewable energy source as compared to the Diesel Generator to minimize the use of the diesel used every day. Owing to the disadvantages of the traditional measurement systems which were based on energy flows, the dynamic characteristics were not observable. A PMU (Phasor Measurement Unit) [111] was proposed where all the quantities measured were stamped by a temporal identifier generated by a Global Positioning System (GPS) clock, which ensured the synchronized measurements for different locations with respect to desired location in Romania. The analysis of data was done and data was partitioned into time series for reduction of data size.

In order to model an efficient AC or DC smart grid, a number of software and open source packages are available to plan the smart grid. One such method for planning approach for smart grid is HOMER [112] which simulates the physical behavior of energy systems and gives their lifecycle cost. Another method of modeling the smart grid was used in the OSeMOSYS (Open Source Energy Modeling System) code [113]. Using the extended code, demand types were prioritized, variable electricity generation, demand shifting, appropriate storage was planned and other control algorithms were tested. A Smart Grid Maturity Model (SGMM) was

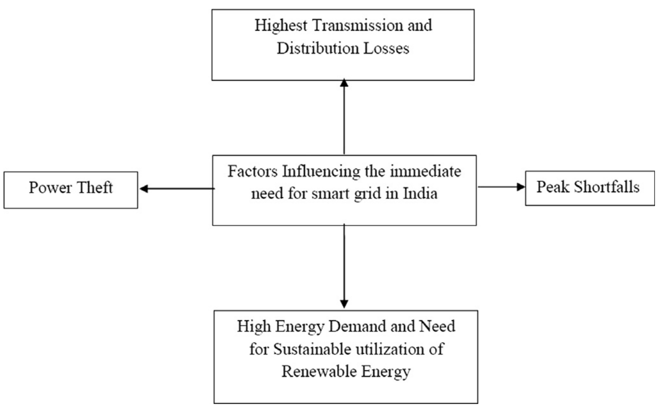

Fig. 13. Necessity of Smart Grid in India [34,119].

Table 1
Comparison of different technologies available for integration, control, monitoring and metering smart grid.

Technologies for integration [27,44]	**Technologies for load control** [16,17]	**Technologies for monitoring** [16]	**Technologies for metering** [16]
Utilization of DC/DC converter MPPT to integrate of PVs and CPVs to smart grid	Clustering algorithm based system for load classification • K-means algorithm • Fuzzy c-means algorithm • Hierarchial clustering algorithm • Self Organisation Mapping	One way communication systems • Less cost • Simple to use • Monitoring and verification of data is not possible	Smart meters • Smart meter is an electronic box with a communication link • Measures electricity consumed with in a time interval
Utilization of bi-directional DC–DC converter to connect batteries used for storage with grid	Decision support and energy management system for building and home energy management	Two way communication systems • High cost • Monitoring and verification of data is possible • Two types of communication systems: wired and wireless communication systems	Advanced Metering Infrastructure (AMI) • AMI is the integration of smart grid with wide area network (WAN), home area network (HAN) and meter data management system (MDMS) • AMI supports distributed management system
Utilization of three phase rectifier bridge and power inverter to integrate biogas, diesel, micro turbine and wind turbine with grid	Backup generators and energy storages for industrial and commercial customers	Wireless communication system • HAN, NAN – coverage range from tens to hundreds of meters (e.g. ZigBee, Wi-Fi) • WAN – coverage range from tens of kilometers (e.g. GPRS, UMTS, LTE)	Energy Management System (EMS) • EMS is a combination of sensors, switches, controls and in build algorithms • Helps in monitoring, analyzing and controlling of various systems and plays a important role in reducing peak demand
		Wired communication system • Powered line communications • Fiber optics • Robust, reliable and need no new infrastructure	Energy Information Systems (EIS) • EIS helps in collection, storage of system performance data and makes it available for end users and utilities • Helps to identify errors and to make decisions

adopted by Department of Energy (DoE) for electric utilities and service providers for software associated with smart grid [114]. Upon modeling the system a Cost Benefit Analysis (CBA) [115] can be done for investment efficiency and for fixing the tariffs.

The smart grid upon modeling has to be checked for the security features [116] too, like availability of uninterrupted power, integrity of communicated information and confidentiality of the user data. Cyber security breaches due to ineffective firewalls in smart grid networks can cause process interruptions [117]. Supervisory Control and Data Acquisition (SCADA) used to control the smart grid are most vulnerable to cyber-attack [118]. STUXNET is a common windows worm [119] discovered in July 2010 is a malware payload designed to target the SCADA system. The attack to smart grid could be from the Advanced Metering Infrastructure (AMI), since they are located outside the consumer or energy utility premises. This vulnerability allows attackers to access the network, break the confidentiality and integrity of the transmitted data and make the service unavailable.

5. Smart grid scenario in developing countries

Smart grids have been gaining much interest in developing countries like India, China and Brazil because of its increased energy efficiency, stability, security, economic improvements and reduced environmental impacts. Renewable energy sources can be effectively integrated to smart grids and moreover, it has estimated that development of smart grids will make opening of 15 million new jobs in China [120]. It has been estimated by DONG Energy (leading energy utilities provider in Denmark) that by adding intelligence to the grids in Denmark would help the system to identify the problems quickly and would reduce the minutes of power lost by 50% [121]. Other countries like China have embarked on a 10 years project to build a smart grid [122] that catapults the power transmission into digital age, securing electricity supplies and boosting energy conservation. India at present have devised scheme called Restructured Accelerated Power Development and Reforms Programme (R-APDRP) to address the upgrading of Indian transmission system by smart grids with 10 billion US $ over five year plan. The factors stressing the immediate need for smart grid in India is shown in Fig. 13. It has also been estimated that by the application of Smart Grid Technology (SGT) to the Nigeria Power System, will make the present grid more efficient and reliable [123]. In [124] outline of European smart grid projects has been discussed and the need for smart grid in Turkey for providing stable, low-cost, reliable power has been stressed.

Application of smart grid in aluminum processing, cement manufacturing, food processing, and industrial cooling plants has been reviewed in [125] with particular emphasis given to automated demand response. The different technologies available for Integration, Control, Monitoring and Metering smart grid is given in Table 1.

6. Conclusion

Smart grid with enhanced integration of DRES and smart demand response systems, enhance the power system stability in distributed networks. Smart grid offers better regulation of the power quality considering the fact that most of all the distributed generators are not load following. Smart grids could inculcate the use of Distributed Flexible AC Transmission Systems (D-FACTS) to control the way power flow distribution through a system by identifying the overloaded element. Smart grids allow the users to control their load consumption and have a greater flexibility of demand and load side management. Smart grid is efficient in intelligently shifting distributed generators from islanding to non-islanding mode according the instantaneous needs and faults using SCADA systems. The smart sensors in the smart grid networks provide automatic fault detection. The Smart grid has to ensure a firewall to prevent it from outside attacks. Although the smart grids have area dependent redundancy but there are single points failure points for end consumers which needs to be addressed. Hence, for developing countries like India with huge renewable energy potential, smart grid is an efficient way to transmit and manage power.

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